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AN ANALYSIS OF TOP ACCIDENTS IN THE FTR USING THE LOS ALAMOS FAILURE MODEL*

by

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ABSTRACT

A new fuel pin failure model (the Los Alamos Failure Model), based on a linear life fraction rule failure criterion, has been developed and is reported herein. Excellent agreement between calculated and observed failure time and location has been obtained for a number of TOP TREAT tests. Because of the nature of the failure criterion used, the code has also been used to investigate the extent of cladding damage incurred in terminated as well as unterminated TOP transients in the FTR.

I. INTRODUCTION

The time and axial location of fuel pin failure, together with the subsequent postfailure-fuel-dispersal phenomena, greatly influence the further course of a transient-over-power (TOP) accident. To assess the potential impact of such an accident, computational tools must be available to predict this transient fuel pin behavior. For this purpose the Los Alamos Failure Model[1] (LAFM) has been developed using a linear life fraction rule[2] as a failure criterion. To test the reliability of the LAFM code, several TOP TREAT tests[3,4] have been analyzed. The results of these analyses, summarized in Table I, have shown excellent agreement between measured and predicted failure times and locations. Hence, the LAFM code is a valuable new tool which can be used in the analysis of fuel pin failure experiments. This paper presents a summary description of the LAFM model along with the results of a series of calculations that have been done to investigate TOP accidents in the fast test reactor (FTR). Both terminated and unterminated transients have been considered. As will be shown, there are several unique features of the LAFM code that make it ideally suited for this type of analysis.

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II. LAFM DESCRIPTION

The LAFM model considers the following mechanisms which are thought to be most important in contributing to fuel pin failure during a TOP accident:

1. fuel-cladding differential thermal expansion,
2. pin pressurization due to transient fission gas release,
3. fission-gas-induced fuel swelling,
4. cladding thermal stress, and
5. cladding melting.

Previous work[5] has shown that fuel vapor pressure is unimportant in causing failure for the range of TOP initiating ramp rates that realistically could be expected in the FTR (especially in irradiated pins). In addition, recent studies[6] have shown that volatile fission products are relatively unimportant except at very high fuel temperatures and low pressures. Thus, the potential effects of these two phenomena are not considered. For very high ramp rate transients (as would be typical in a loss-of-flow driven transient-overpower event, for example), the potential effects of fuel vapor pressure will have to be considered.

The failure criterion used in LAFM is based on a linear life fraction rule.[2] This permits calculating the time and axial location of failure in unterminated transients as well as estimating the amount of damage done to the cladding in transients that do not result in failure. The use of this criterion requires that the fuel-cladding boundary pressure and the cladding temperature be calculated.

To calculate the fuel-cladding boundary pressure, the fuel in a typical axial pin section (Fig. 1) is described by:

1. a central hydrostatic region (initial center void and any molten fuel),
2. an elastic uncracked region,
3. an elastic cracked (closed radial cracks) region, and
4. an elastic cracked (open radial cracks) region.

The relative change in size of these regions as melting, cracking, and crack closure occur during the transient is calculated. In addition to these radial cracks, an initial circumferential fuel crack may be specified to analyze experiments in which such cracks are observed. Previous studies[7] have shown the importance of considering these fuel cracks in TOP analysis.

Currently, inelastic fuel behavior is not explicitly modeled. Fuel creep, however, is potentially a very important mechanism for relieving the cladding stress .] from fuel-cladding differential thermal expansion. This is especially for high fuel temperatures, because recent measurements have shown that high temperature (~2775 K) creep rate of oxide fuel is about two orders of magnitude higher than would be expected from an extrapolation of the available low temperature creep data.[8] To approximate this very rapid high temperature creep behavior, the model does include a cutoff temperature above which fuel creep is sufficiently rapid to be considered instantaneous relative to the accident time scale of interest. Thus, above this cutoff temperature the fuel is treated as being strengthless.

For the stress analysis, the cladding is treated as an elastic-plastic thick-walled cylinder with the plastic behavior described through the use of the Tresca yield criterion ($Y = \sigma_\theta - \sigma_r$). Cladding creep is not considered in the analysis. The use of the Tresca yield criterion, as indicated, implies that the hoop stress is the largest tensile stress in the cladding, and that the axial stress lies somewhere between the radial and hoop stresses. Through the use of this criterion, a relatively simple solution for the fuel-cladding boundary pressure is obtained even when the strain-hardening behavior of the cladding is completely arbitrary. Details of this result, as well as other aspects of the model, may be found in Reference 1.

III. ANALYSES OF TRANSIENT OVERPOWER EVENTS IN THE FTR

Previously reported calculations using the LAFM code have concentrated on the analysis of TOP TREAT tests.[1,7] These calculations were intended to test the reliability of LAFM failure predictions. The results of these calculations, summarized in Table I, show good agreement between measured and predicted failure times with an average error of 30 ms for the 3$/s transients and 80 ms for the 50¢/s transients. In this paper, the LAFM code is used to investigate cladding damage and failure in hypothetical TOP accidents in the FTR. Initiating ramp rates of 3$/s, 50¢/s, and 5¢/s are considered.

LAFM is capable of discriminating among several fuel microstructures and their mechanical response and can treat the effects of fluence and burnup; hence, two distinct fuel pin types (high and intermediate power) are considered in the analyses, both of which are characteristic of beginning-of-equilibrium cycle cores. The fuel pins have a peak linear heating rate of 39.7 and 32.2 kW/m with burnups of 18.5 and 35 MWd/kg respectively. The salient characteristics of these fuel pins at steady state operating conditions (determined using the SIEX computer code[9]) are given in Table II.

TABLE I

COMPARISON OF LAFM PREDICTIONS AND EXPERIMENTAL RESULTS FOR TOP TREAT TESTS

Test	Observed Failure Time (s)	Predicted Failure Time (s)	Observed Maximum Strain (%)	Predicted Maximum Strain (%)
E6	9.18	9.195	*	0.95
H4	6.69	6.68	*	0.46
HUT5-5A	-	-	0.068	0.072
HUT5-5B	11.00	11.08	*	0.44
HUT5-3A	8.95	8.80	*	0.12
HUT3-3A	-	-	0.51	0.57
HOP3-2A	-	-	0.13	0.15
HOP3-2B	-	-	0.30	0.26
HUT3-5A	-	-	0.08	0.06
HOP3-1A	-	-	0.00	0.03
HUT3-5B	9.74	9.675	*	0.74

*Strain could not be measured because of test pin destruction.

TABLE II

STEADY STATE FUEL PIN CHARACTERISITICS*

	Peak Linear Heat Rate (kW/m)	Peak Burnup (MWd/kg)	Peak Cladding Fluence ($x10^{22}n/cm^2$)	Radial Fuel-Cladding Gap (m)	Center Void Radius (m)
High Power Pin	39.7	18.5	3.0	0.0	5.0×10^{-4}
Intermediate Power Pin	32.2	35	6.5	1.9×10^{-6}	4.1×10^{-4}

*At the axial midplane

The analysis of FTR overpower transients can be divided into two parts: the analysis of terminated (both primary and secondary trip) transients and the analysis of unterminated transients. For the terminated transients, primary trip was assumed to occur at 15% overpower and secondary trip was assumed to occur at 25% overpower, with a 200 ms instrumentation delay[10] in each case. The resulting power transients are shown in Fig. 2. The use of a life fraction failure criterion in LAFM makes the code ideally suited for the analysis of terminated transients. Three separate measures of the safety margin in the primary and secondary trip settings are then available: time-to-failure in the unterminated transient, permanent cladding strain, and cladding life fraction consumed in the transient.

For each fuel pin, a total of nine calculations (three initiating ramp rates with three degrees of protective system response) was performed. For the unterminated transients, the effect of high temperature fuel creep was estimated by considering the fuel to be strengthless above 2700 K. For the terminated transients, however, the effect of high temperature fuel creep was not included. This provides an extra margin of conservatism (life fraction will be overpredicted), because fuel creep tends to relieve the cladding stress. The cumulative life fraction and permanent cladding strain were computed as a function of time for each case. The results of these calculations are presented in Table III (final life fraction) and Table IV (maximum permanent cladding strain).

IV. DISCUSSION OF TERMINATED TRANSIENTS

Tables III and IV show that, for all combinations of initiating ramp rate and fuel type, both the primary and secondary trip settings lead to a negligible amount of cladding damage being calculated during the transient. In each case, no permanent cladding strain is calculated and the maximum cladding life fraction is calculated to be on the order of 10^{-9} (failure occurs when the life fraction equals 1.0). Furthermore, the small life fraction that is calculated in each case peaks at the top of the pin, indicating that the cladding stress at the axial midplane resulting from fuel-cladding differential thermal expansion is relatively small. In that case, the axial life fraction distribution is strongly dominated by the axial cladding temperature distribution. Because this peaks at the top of the pin, the cladding life fraction also peaks at the top of the pin.

The third measure of the safety margin in the overpower trip settings is the incremental time from reactor scram (including 200 ms instrumentation delay) to the calculated failure time in the unterminated transient. As shown in Fig. 2, primary trip occurs at ~3 s into the 5¢/s transient, and secondary

TABLE III

LIFE FRACTION CONSUMED DURING TRANSIENTS

	Transient	Peak Life Fraction: Primary Trip	Secondary Trip	Unterminated*
High Power Pin	3$/s	$3x10^{-10}$	$9x10^{-10}$	0.62 s (.86)
	50¢/s	$6x10^{-10}$	$1x10^{-9}$	3.15 s (.64)
	5¢/s	$1x10^{-9}$	$3x10^{-9}$	21.6 s (.64)
Intermediate Power Pin	3$/s	$8x10^{-10}$	$9x10^{-10}$	0.61 s (.75)
	50¢/s	$8x10^{-10}$	$8x10^{-10}$	3.47 s (.58)
	5¢/s	$9x10^{-10}$	$2x10^{-9}$	29.5 s (.58)

*Failure time (relative axial location - X/L)

TABLE IV

PERMANENT CLADDING STRAIN RESULTING FROM TRANSIENTS

	Transient	Peak Permanent Strain (%): Primary Trip	Secondary Trip	Unterminated
High Power Pin	3$/s	0.0	0.0	0.38
	50¢/s	0.0	0.0	0.12
	5¢/s	0.0	0.0	0.10
Intermediate Power Pin	3$/s	0.0	0.0	0.18
	50¢/s	0.0	0.0	0.05
	5¢/s	0.0	0.0	0.04

trip occurs at ~6 s into the transient. Since pin failure in the unterminated 5¢/s transient (for the high power pin, for example) is not calculated to occur until 21.6 s, this provides a time-to-failure safety margin of 18 s and 15 s for the primary and secondary trip settings, respectively. Similarly, time-to-failure safety margins of 2.75 s and 2.6 s for the 50¢/s transient and .385 s and .32 s for the 3$/s transient are calculated. The only terminated transient that was calculated to come close to resulting in cladding damage is the 3$/s transient terminated by secondary trip. For the $3/s case, secondary trip occurs at 260 ms into the transient. This is only ~10 ms before fuel-cladding differential thermal expansion near the axial midplane results in a small value of permanent cladding strain being calculated (in the unterminated transient). The calculated peak life fraction at that time, however, is still very small ($\sim 10^{-6}$).

V. DISCUSSION OF UNTERMINATED TRANSIENTS

For the analysis of unterminated overpower transients, the important calculated results, the time and axial location of pin failure, are presented in Table III for both the high and intermediate power pins. Before discussing these results in detail, it is instructive to consider the differences between the two pins that would affect the calculated time and axial location of failure. The most obvious difference is, of course, the initial pin power and temperature. The lower power and initial temperature in the intermediate power pin means that it will take longer for that pin to heat up significantly during a transient . Thus, for any given transient, fuel melting would start later, and the cladding would be stronger (cooler).

Aside from the initial pin power and temperature, the two key parameters are the initial fuel-cladding gap and the cladding fluence. Because the initial fuel-cladding gap in the high power pin is much smaller than in the intermediate power pin, fuel-cladding differential thermal expansion should be more important in the higher power pin leading to earlier and lower failure. However, the cladding fluence is much higher in the intermediate power pin (peak value of 6.5 n/cm^2 in the intermediate power pin versus 3.0 n/cm^2 in the high power pin). Thus, earlier failure is expected in the intermediate power pin, because the higher fluence cladding is considerably weaker.

The foregoing discussion points out the difficulty in making intuitive conclusions about the relative pin failure behavior of different fuel pins. Because there are many competing factors that influence pin failure, a mechanistic calculation is needed to determine how these various factors interact.

Several conclusions can be drawn from the unterminated transient results in Table III. One very noticeable aspect of these results is the lower axial failure location in the intermediate power pin. This demonstrates the greater importance of fuel-cladding differential thermal expansion (at the time of failure) in the intermediate power pin. In the high power pin, the temperature distribution is such that less fuel-cladding differential thermal expansion is calculated. Thus, in the high power pin the (assumed) axially uniform pressure in the central hydrostatic region is more important (at the time of failure), and failure is shifted towards the hotter region near the top of the pin.

The other dominant aspect of these results is the higher failure location in the faster transient. The 50¢/s transient and especially the 5¢/s transient are sufficiently slow for the coolant flow to keep the cladding temperature low enough for differential thermal expansion to be important. In the 3$/s transient, however, differential thermal expansion is important only early in the transient. If failure does not occur at that time, the cladding and coolant temperature increase very rapidly (relative to the ability of the coolant flow to cool the cladding). In that case, the high cladding temperature minimizes the importance of fuel-cladding differential thermal expansion, and fission gas pressurization becomes the dominant failure mechanism. This shift in failure mechanisms can be seen by looking at the axial life fraction distribution in the 3$/s transient prior to the time of failure. For the high power pin, for example, the peak life fraction at 10 ms prior to failure occurs at an axial height of X/L = .64 even though failure is eventually calculated to occur at X/L = .86.

VI. CONCLUSIONS

The previous two sections demonstrate the usefulness of the LAFM code for the analysis of both terminated and unterminated overpower transients. With the LAFM code, it was possible to show that 3$/s, 50¢/s, and 5¢/s transients terminated by the secondary trip point (25% overpower) result in negligible calculated cladding damage. The analysis of the unterminated transients indicates how the competing failure mechanisms of fuel-cladding differential thermal expansion and fission gas pressurization interact to determine the failure location.

Several unique features of the LAFM program make it ideally suited for analyses such as these. The program is capable of treating adequately both the effects of fluence and burnup and the mechanical effect of various microstructures. The use of the life fraction failure criterion makes possible for the first time the accurate evaluation of cladding damage in transients terminated short of failure.

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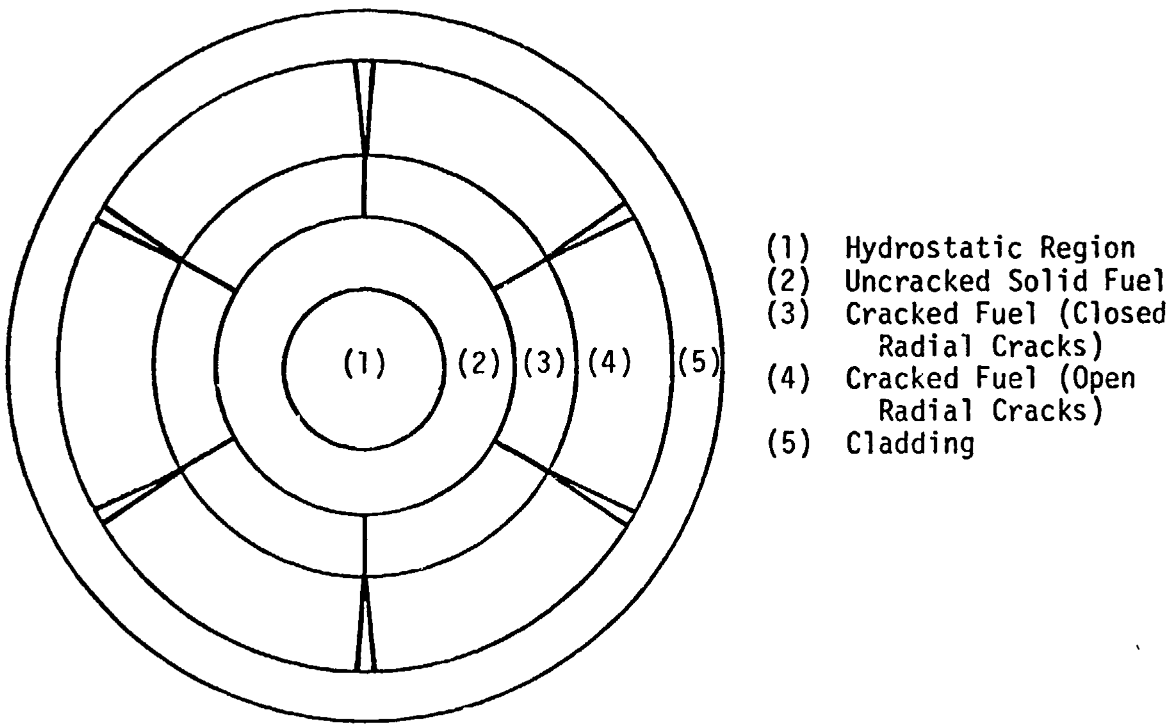

Fig. 1.
Fuel pin characterization.

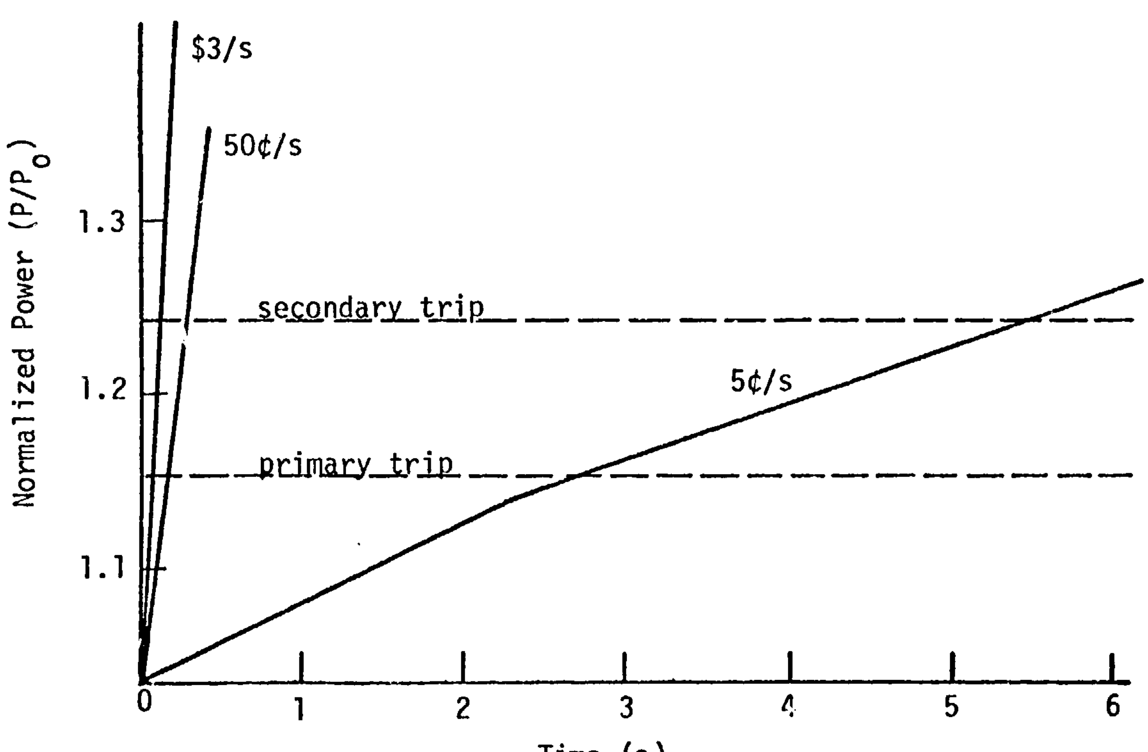

Fig. 2.
Hypothetical FTR power transients.